

Acoustic Noise and Onset of Sodium Cavitation in Venturi

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ABSTRACT

The present paper describes the acoustics noise characteristics and cavitation onset conditions of flowing liquid sodium in a venturi. The simplified cavitation test section is a venturi made of SS-316 with 6.5 mm inner diameter and 20 mm in length. The experiments were conducted at sodium stagnant pressure in the expansion tank of 0.6-0.18 MPa and temperature of 200-400°C. As a result it was found that the noise intensity increased greatly at cavitation inception and became constant in developed cavitation (lower K). Cavitation coefficient at onset of cavitation was nearly equal to unity. However, an increase in temperature shifted the cavitation coefficient to a value a little higher than unity. It also showed that by increasing the stagnant pressure, the inception velocity at the venturi also increased. For every temperature rise, there is a difference in the noise intensity between no cavitation and cavitation conditions over a range of frequencies. At higher temperature (300 and 400°C) the cavitation noise became unstable, which may probably be caused by the increasing amount of cavitation bubbles due to the higher vapor pressure.

1. Introduction

Sodium-cooled fast reactor (SFR) is one of the proposed future nuclear reactors known as Generation IV nuclear reactors. It is fast spectrum reactor using a closed fuel cycle with full actinide recycle. Its main missions are to reduce the physical demand on repositories, and utilize the entire natural resource for fissionable materials. At present, SFRs are considered as the most technologically developed of the six Gen-IV systems, such as Lead-cooled reactor (LFR), High temperature reactor, etc. In some countries, such as France, Japan, Germany, the U.K., Russia or the U.S.S.R., and the U.S., there are SFRs that have been built and operated. There are demonstration plants ranged from 1.1 MWth (at EBR-I in 1951) to 1200 MWe (at SuperPhenix in 1985), and some other sodium-cooled reactors today in Japan, France, and Russia (Till *et al.*, 1996; Kiryushin *et al.*, 2002; King *et al.*, 2002). The deployment date for sodium-cooled fast reactor is estimated around 2020 (Roglan *et al.*, 2002).

One of the key issues in fluid-dynamic design of the sodium-cooled fast reactors is inhibition of cavitation and/or its influence. Cavitation can be regarded as “an ebullition process that takes place if the bubble grows explosively in an unbounded manner as liquid rapidly changes into vapor. This situation occurs when the pressure level goes below the vapor pressure of the liquid” (Fitch, 2002). The influence is classified into fluid-dynamic, mechanical, and core neutronics performances as follows: the occurrence of cavitation affects fluid-dynamic performances of flow regulating mechanisms in inner structure of reactor vessel; the collapse of cavitation bubbles produces shock waves that damage the edges of orifices, which changes flow rate distribution in core; the shock waves also damage structural material and piping walls; vibrations due to cavitation cause metal fatigue of piping systems; and the entry of cavitation bubbles into core causes

instability of core reactivity. Cost-down effort in design leads to more compact reactor vessel and components, which makes the cavitation to occur readily because of higher coolant velocity in coolant flow circuits. According to Kale *et al.* (2004), “the damage of the structural parts in the vicinity of the cavitating zone and its severity is found to be 1.5 to 2 times more severe compared to that in water, and also the cavitation phenomenon which results in producing vapor cavities is not acceptable in case of fuel element passages, due to the resulting overheating of fuel clad and its implications”.

Furthermore, most of the experimental studies for investigating the sodium cavitation phenomenon in designing the sodium-cooled fast reactors were conducted using water as simulant fluid. Therefore, there are scarcities of data for sodium cavitation nowadays. These lacks of data can be a major obstacle in evaluating the onset of cavitation and its influence in sodium-cooled fast reactor. The present study is intended to understand the phenomenon of cavitation in liquid sodium as well as its acoustic noise characteristics.

2. Sodium Loop and Test Section

2.1. Description of sodium loop

Liquid sodium cavitation experiment was conducted using a sodium loop facility at Sukegawa Electric Co., Ltd. shown in Fig. 1. This sodium loop facility can be operated up to 500°C and maximum sodium flow rate of 20 L/min. It consists of a test section, an electromagnetic pump (EMP), two electromagnetic flow rate meters (EMFs), a heater, a cooler, a cold trap and an expansion tank. The heater and expansion tank control the temperature and the stagnant pressure of the sodium loop at the required experimental conditions, respectively. Argon gas was used as cover gas inside the

expansion tank. The flow rate of the liquid sodium was measured using the EMF at the bottom part of the loop. For the purpose of this experiment, the cold trap and EMF-2 shown by the green lines were not used.

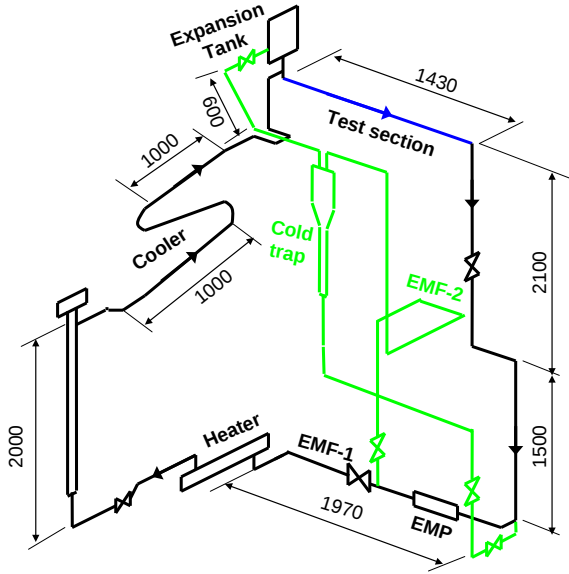


Fig. 1. Schematic of the sodium loop facility

2.2. Description of test section

The test section of the loop was made from SS-316. It consists of a gas injector, a venturi, a wave guide rod and a static pressure tap. A gas injector is mounted at the test section to inject argon gas in the flowing liquid sodium, although it was not used in the present experiment. The venturi is used to create cavitation bubbles inside the liquid sodium that passes through it. The acoustics noise signals generated from the cavitation bubbles were measured by using an accelerometer (Ono Sokki NP-2710) installed at the bottom part of the wave guide rod. By definition, an accelerometer is a sensor that could convert mechanical vibration signals into electrical signals. The magnitude is proportional with the vibratory acceleration. This type of accelerometer could be used directly just by attaching it to the test object, hence no reference point of measurement is needed anymore. The electrical signal coming from the accelerometer is generated when a force is applied to it. Ono Sokki NP-2710 could be classified as shear-type accelerometer based on the method of the applying force. In this type, charge signal will be released when there is a shear-type force applied to the piezoelectric crystal element of the sensor. The downstream pressure of the test section was measured by using a pressure transducer (Ashcroft GC-51) connected to the pressure tap.

In order to obtain the high flow rate necessary to generate cavitation conditions inside the liquid sodium, the inner diameter of the venturi is reduced to 6.5 mm with the maximum sodium flow rate of 20 L/min. The choice of 6.5 mm inner diameter of the venturi is to counter balance the effect of the pressure drops along the liquid sodium test section part and also the pump head of the electromagnetic pump. The pressure drops along the test section were calculated analytically using the following formula:

$$\Delta P = (K_c + K_e) \frac{\rho}{2} V_0^2 + \frac{0.3164}{Re^{0.25}} \frac{\rho}{2} V_1^2 \frac{L}{D_1} \quad (1)$$

where ΔP is the pressure drop along the test section part, K_c is the contraction coefficient, K_e is the enlargement coefficient,

ρ is the sodium density, V_0 is the sodium velocity at venturi part, V_1 is the sodium velocity at downstream region, Re is the Reynold's number, L is the length of the test section, and D_1 is the inner diameter of the downstream region.

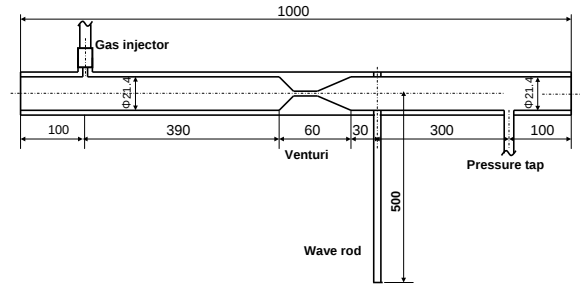


Fig. 2. Liquid sodium test section part

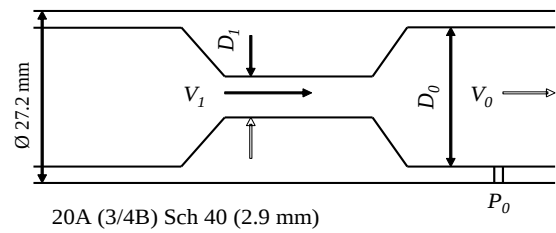


Fig. 3. Venturi of the test section

3. Experimental Procedures

The experiments were conducted at sodium stagnant pressure inside the expansion tank of 0.6~0.18 MPa-a and temperature of 200~400°C. The detailed experimental procedures can be explained as follows:

- 1) At the beginning, the loop was circulated with a desired level of experimental temperature.
- 2) The EMP was turned off. Then, the pressure at the expansion tank was controlled to a desired level of experimental conditions by injecting argon gas.
- 3) When the experimental conditions were all reached, the EMP was turned on again to circulate the liquid sodium.
- 4) The EMP voltage was increased gradually to the desired cavitation conditions and the experimental data were collected.

Before the experiments, some components of the sodium loop facility were calibrated first. The components that were calibrated are pressure transducer and electromagnetic flow rate meter (EMF).

Tables 1, 2, and 3 show the characteristic of the pressure transducer, acoustics noise sensor, and the detailed experimental conditions, respectively.

Table 1. Pressure transducer characteristics

Specification (pressure gauge)		Specification (diaphragm)	
Pressure range	-0.1~0.1 MPa-g	Diameter	110 mm
Output	4~20 mA	Lower flange material	SUS 316L
Maximum temperature	200°C	Upper flange material	SUS 316

The static pressure of the liquid sodium downstream was sensed by the diaphragm connected at the pressure tap and transmitted along the silicon oil tube to the pressure transducer. This silicon oil tube also acts as a heat resistance to keep the maximum allowable temperature of the pressure gauge below 200°C, as shown in Fig. 4.

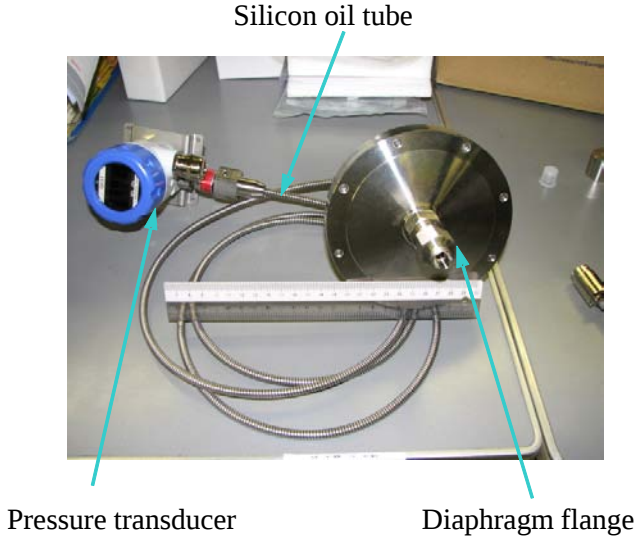


Fig. 4. Photograph of diaphragm type pressure gauge

Table 2. Sensor characteristics

Sensor brand and type	Ono Sokki NP-2710
Sensitivity (pC/m/s ²)	0.31±10%
Transverse sensitivity	Within 5%
Capacitance	~340 pF
Frequency response*	fc~10kHz±5% fc~20kHz±3dB
Resonant frequency	~50kHz
Peak operating (m/s ²)	22,600
Shock survivability (m/s ²)	98,000
Operating temperature range (°C)	-70 ~ +260

*fc depends on the time constant of the connected amplifier.

$$fc = \frac{1}{2\pi RC}$$

Table 3. Experimental conditions of the cavitation test

Temperature (°C)	Stagnant Pressure (MPa-absolute)
200	0.06~0.18
300	0.08~0.18
400	0.08~0.18

4. Results and Discussions

The results of the experiments are presented in Fig. 5 to 18. Fig. 5 and 6 show the result of the noise intensity over cavitation coefficient K at 300 and 400°C. The results show that the noise intensity is relatively low when there is no cavitation in the venturi region (K is higher than unity). The noise intensity begins to rise rapidly when K approaches unity (onset of cavitation). Under developed cavitation condition (K is lower than unity), the noise intensity is relatively stable without changing dramatically. The stagnant pressure at the expansion tank has no effect on the noise intensity in developed cavitation conditions. The noise intensity at 400°C

has no significant differences with that at 300°C, which is around 43 dB. The onset of cavitation was determined by hearing the sound of the cavitation test section and checking the spectrum analyzer monitor. It was concluded that cavitation occurred (onset of cavitation) when there was a rise in the amplitude of the spectrum analyzer, and rapid knocking sounds in the test tube. The determination of the onset condition is rather subjective since sodium is opaque.

The cavitation coefficient K in this experiment is derived from the Bernoulli's equation for incompressible flow.

$$P_1 + \frac{\rho}{2}V_1^2 = P_0 + \frac{\rho}{2}V_0^2 \quad (2)$$

where P_1 is the static pressure at venturi, ρ is the liquid sodium density at given temperature, V_1 is the liquid sodium velocity at venturi region, P_0 is the static pressure at downstream, and V_0 is the liquid sodium velocity at downstream region. If P_1 is close to the saturation pressure P_v of the liquid sodium, then the cavitation coefficient K can be expressed as

$$K = \frac{P_0 - P_v}{\frac{\rho}{2}(V_1^2 - V_0^2)} \quad (3)$$

and for $V_1 \gg V_0$

$$K \approx \frac{P_0 - P_v}{\frac{\rho}{2}V_1^2} \quad (4)$$

where P_v is the sodium saturation pressure at given temperature. According to the theory, cavitation starts to occur when cavitation coefficient K is equal to unity. From the data obtained, it is clear that cavitation coefficient K can be used as a raw prediction of the onset cavitation conditions.

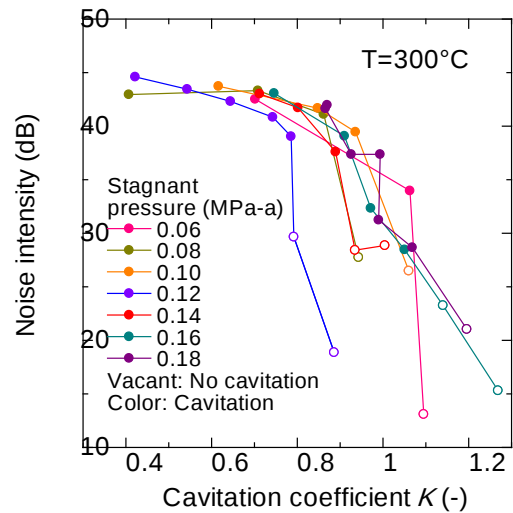


Fig. 5. Noise intensity vs cavitation coefficient at 300°C

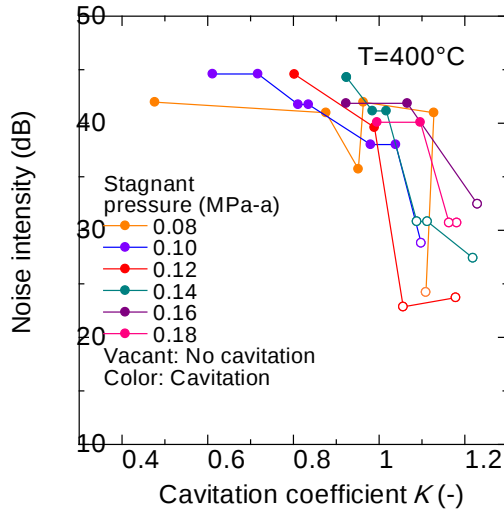


Fig. 6. Noise intensity vs cavitation coefficient at 400°C

Figs. 7, 8 and 9 show the results of no cavitation and occurrence of cavitation on the map of the venturi velocity vs cavitation coefficient at 200, 300 and 400°C, respectively. For every temperature rise, it is apparent that the stagnant pressure in the expansion tank has influence on the onset cavitation velocity in the venturi. The velocity in the venturi increases with the increase of the stagnant pressure conditions. The velocity becomes relatively stable in the developed cavitation conditions. Cavitation coefficient at the onset of cavitation was nearly equal to unity. However, an increase in temperature shifted the cavitation coefficient to a value a little higher than unity. From these figures it can be concluded that the formation of the cavitation bubbles is suppressed at higher stagnant pressure, therefore the onset cavitation velocity in the venturi increases. It is noted also from the figures that there are two distinct regions, the no cavitation region ($K > 1$), and the cavitation region ($K < 1$).

These figures also show that if the cavitation coefficient below the value of unity, the cavitation velocity in the venturi is relatively constant. This is similar to the phenomenon of the critical or the choked flow. In the critical or choked flow phenomenon, the decrease in the downstream pressure below a certain level of critical pressure does not significantly increase the flow rate. For cavitation in a venturi, the critical flow phenomenon is caused by the decrease of the sound velocity in the liquid sodium due to the formation of cavitation bubbles.

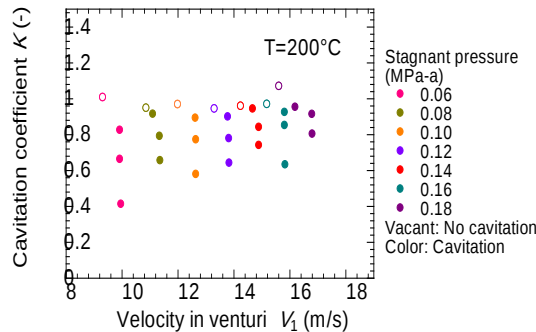


Fig. 7. Cavitation coefficient K vs venturi velocity at 200°C

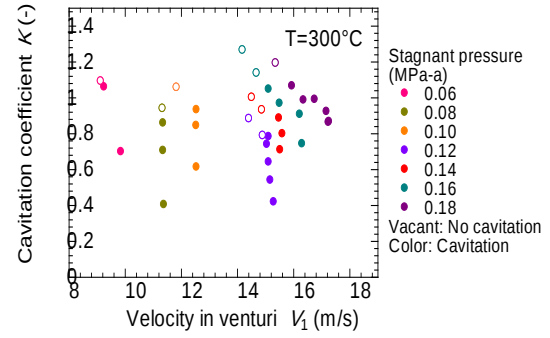


Fig. 8. Cavitation coefficient K vs venturi velocity at 300°C

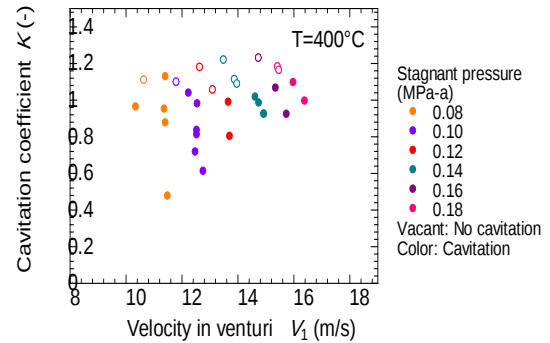


Fig. 9. Cavitation coefficient K vs venturi velocity at 400°C

Fig. 10 shows the resonance frequency of the test section at 200°C and 0.12 MPa-a. This figure was obtained from hitting the test section by hammer several times when the electromagnetic pump was turned off. The resonance frequencies of the test section are indicated by the peaks of noise intensity around 1000, 3000, 5000, 9000, and 20,000 Hz as shown in Fig. 10. The noise intensities have the significant increase in the high frequency regions than in the low frequency regions.

Figs. 11 to 14 show the results of the noise intensity over frequency at different temperature and stagnant pressure conditions at 200°C. The results show that an increase in noise intensity is significant at higher frequencies (above 10,000 Hz) than at lower ones. During the no cavitation conditions, the noise intensity at the higher frequencies is relatively lower compared to that at the lower ones. When cavitation starts to occur (intermittent cavitation), the noise intensity at the higher frequencies starts to increase more than at the lower ones. At developed cavitation conditions, the noise intensity at the higher frequencies is almost similar to that at the lower ones. This indicates that there are no significance differences in the magnitude of the noise intensity over the entire frequencies spectrum when cavitation is in the developed conditions. The change of the stagnant pressure in the expansion tank from 0.08 to 0.18 has no effect on the magnitude of the noise intensity. It can be concluded that the magnitude of cavitation noise intensity at 200°C is independent of the stagnant pressure changing. These figures also show some resonance peaks similar with those obtained in Fig. 10.

Figs. 15 and 17 show the results at 300°C. The results at 300°C are almost similar with those at 200°C, except at 0.14 and 0.18 MPa-a. At 0.08 MPa-a, the increase of the noise intensity at lower frequencies are lower than that at higher frequencies. While at 0.14 and 0.18 MPa-a, the cavitation noise intensity increases both at lower and high frequency regions. Therefore, at 0.14 and 0.18 MPa-a the noise intensity of no cavitation and developed cavitation conditions can be distinguished clearly by observing the magnitude change of the noise intensity at low and high frequency regions. The

similar resonance peaks can also be seen clearly at 300°C as in 200°C.

At 400°C and different stagnant pressure in the expansion tank (Figs. 18 to 20), there are clear distinctions on the noise intensities at no cavitation and cavitation conditions. When there is no cavitation, the magnitude of the noise intensity is relatively low (around -70 dB) both at low and high frequency regions. If cavitation starts to occur in the venturi, the noise intensity starts to increase to a higher value (around -45 dB), both in low and high frequency regions.

For 400°C, the noise intensity becomes unstable. It means that sometimes the magnitude of the noise intensity was large (similar to the noise generated by the developed cavitation conditions) for a relatively long time, but then the noise became relatively low (similar to the noise generated by the no cavitation conditions). These instabilities of the noise intensities were probably caused by the increasing amount of cavitation bubbles due to the higher vapor pressure. Further examinations are needed to understand the cause of these instabilities at high temperature (400°C).

From the data obtained at 200, 300, and 400°C, it can be concluded that the stagnant pressure change at the expansion tank does not affect the magnitude of the noise intensity at 200, 300, and 400°C. Therefore, it is independent of the stagnant pressure level.

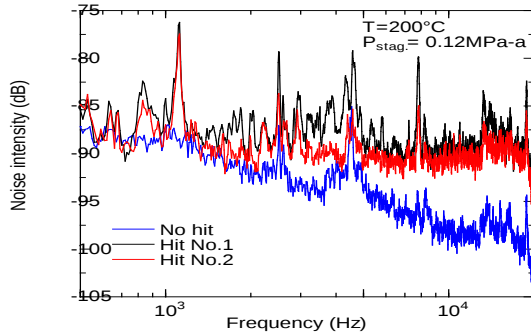


Fig. 10. Resonance frequency of the test section

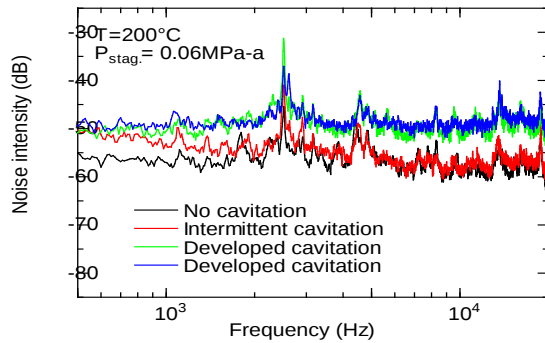


Fig. 11. Noise intensity vs frequency at 200°C and 0.06 MPa-a

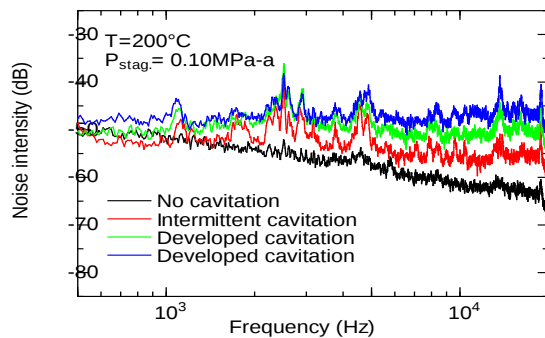


Fig. 12. Noise intensity vs frequency at 200°C and 0.10 MPa-a

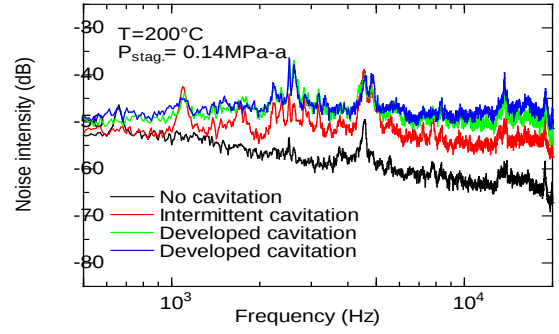


Fig. 13. Noise intensity vs frequency at 200°C and 0.14 MPa-a

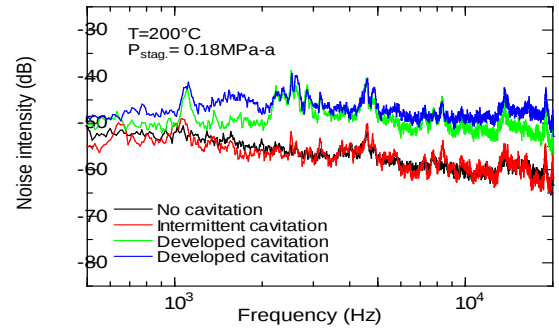


Fig. 14. Noise intensity vs frequency at 200°C and 0.18 MPa-a

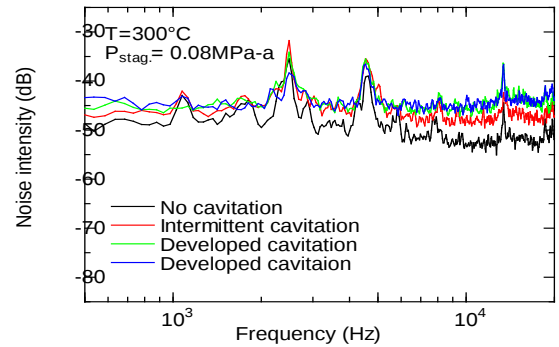


Fig. 15. Noise intensity vs frequency at 300°C and 0.08 MPa-a

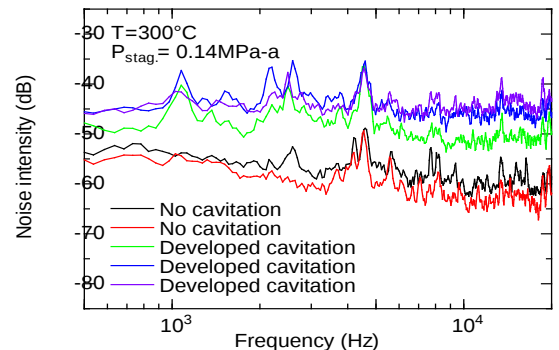


Fig. 16. Noise intensity vs frequency at 300°C and 0.14 MPa-a

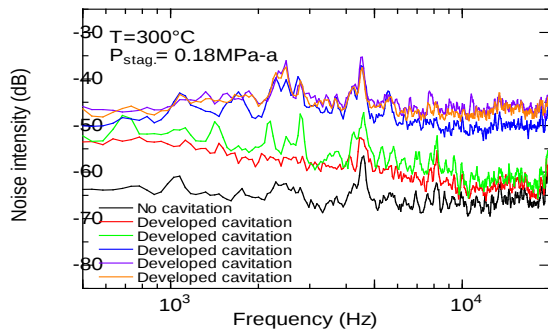


Fig. 17. Noise intensity vs frequency at 300°C and 0.18 MPa-a

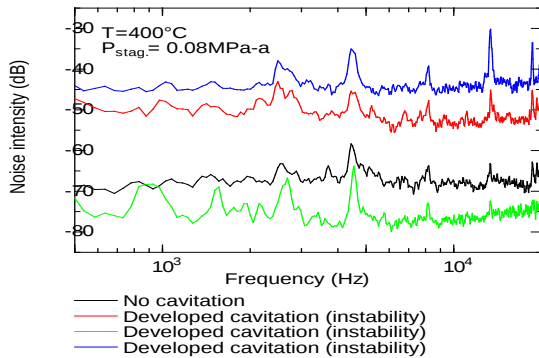


Fig. 18. Noise intensity vs frequency at 400°C and 0.08 MPa-a

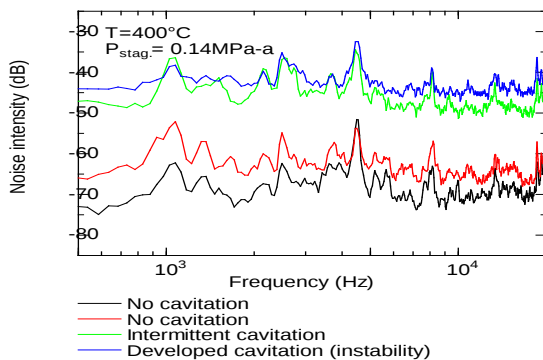


Fig. 19. Noise intensity vs frequency at 400°C and 0.14 MPa-a

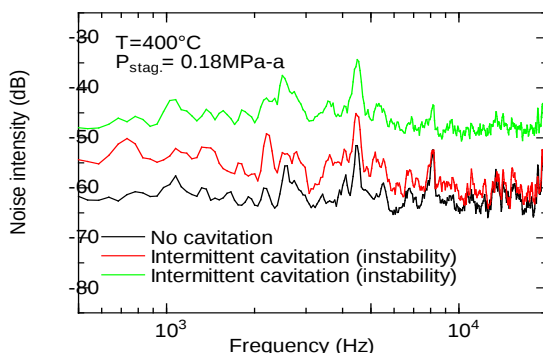


Fig. 20. Noise intensity vs frequency at 400°C and 0.18 MPa-a

5. Conclusions

Sodium cavitation inception conditions were clarified for a venturi. The test section is a venturi with 6.5 mm in inner diameter and 20 mm in length. The experiments were conducted at sodium stagnant pressure in the expansion tank

of 0.6-0.18 MPa and temperature of 200-400°C. The following conclusions have been reached from the experimental results:

- 1) The noise intensity starts to increase dramatically when cavitation occurs inside the test section.
- 2) The stagnant pressure at the expansion tank has no effect in the magnitude of the cavitation noise intensity.
- 3) The stagnant pressure at the expansion tank has clear effect on the onset cavitation velocity in the venturi. The higher the stagnant pressure, the faster the velocity in the venturi to initiate cavitation.
- 4) At 200°C, an increase in the noise intensity is larger at higher frequencies than at lower ones in intermittent cavitation conditions, and the magnitude becomes relatively similar between low and high frequency regions in developed cavitation conditions.
- 5) At 300°C and lower stagnant pressure condition, the increase of the noise intensity in developed cavitation conditions is similar to that as in 200°C. While at higher stagnant pressure conditions, the increase can be seen both in low and high frequency regions.
- 6) At 400°C and no cavitations, the noise intensity is relatively low both in low and high frequency regions. When cavitation starts to occur, the noise intensity increases both in low and high frequency regions.
- 7) Instability conditions occur at high temperature condition (400°C) in the sodium loop. It may be caused by the increasing amount of cavitation bubbles due to the higher vapor pressure. Further examinations are needed to understand the cause of these instabilities at high temperature.

From this experiment it is recommended to conduct another cavitation research with different parameters to give a better understanding in the liquid sodium cavitation phenomenon.

Acknowledgements

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